**REPORT for OBJ2.TASK 4: DETERMINING INFILTRATION RATES**

To: MPCA

From: The Kestrel Design Group Team (The Kestrel Design Group Inc, with Dr. William Hunt, PE, Ryan Winston, PE, Dwayne Stenlund – Minnesota Department of Transportation, Dr. John Gulliver, PE – University of Minnesota)

Date: July 31, 2013

Re: Contract CR5332 Objective 2 Task 4

**SCOPE**

**Obj2.Task 4: Determining Infiltration Rates:**

Develop guidance and recommendations for determining soil infiltration rates within infiltration and bioretention BMPs by performing the following:

1. Review literature and new research to identify existing methods for determining soil infiltration rates. The review shall include but not be limited to use of soil boring information, single and double ring infiltrometers, and disk permeameters, including the modified Philip-Dunne permeameter used by the University of Minnesota, for determining soil infiltration rates. Case studies shall be identified.
2. Explore the need for infiltration correction factors to account for decreased infiltration rate over time compared to infiltration rates measured at the time of BMP construction. Review recent literature on the use of correction factors. Review Table 12.INF.8 (Total Correction Factors Divided into Measured Infiltration Rates) and section 7.1, Step 6 in the Manual to determine if modifications are needed.
3. Prepare and submit a Technical memo summarizing the results of the literature review. The memo shall include, but not be limited to, the following:
   * 1. Guidance summarizing the suitability of different methods for investigating soils;
     2. Recommendations for the number and depth of borings needed to estimate an average infiltration rate within the BMP, including cost and uncertainty information. Uncertainty refers to a quantitative estimate of the confidence in the determination of infiltration rate based on the soil information collected;
     3. Recommendations for the number of infiltration rate measurements needed to establish an average infiltration rate within the BMP, including costs and uncertainty information. Uncertainty refers to some quantitative estimate of the confidence in the determination of infiltration rate based on the soil information collected;
     4. A recommendation about whether there is a maximum allowable infiltration rate for design and what the connection is between maximum infiltration rate and maximum basin depth; and
     5. Recommendations on modifications to Table 12.INF.8 and Section 7.1, Step 6 (regarding infiltration correction factors) in the Manual.

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**REPORT (note: report is supplemental to meeting minutes from bioretention workshops held February 26 and 27, 2013)**

**Background on Soil Infiltration Rate Testing**

During rainfall, a saturated zone forms quickly at the soil surface as rainfall causes surface ponding. The wetting front advances downward into the soil as infiltration continues, causing an increase in the moisture content as a function of depth (Hillel, 1982). A transmission zone between the saturated zone and the wetting front conveys water deeper into the soil profile. Infiltration testing is meant to mimic these natural processes and informs the design of stormwater infiltration practices. During an infiltration test, infiltration rate decreases over time as the soil becomes saturated. Infiltration rate tends to asymptotically approach the saturated hydraulic conductivity (the maximum water transmission rate of the soil) after long periods of infiltration, though entrapped air in the soil never results in perfectly saturated flow in the vadose zone. Since infiltration rate varies both spatially and temporally as a result of being dependent on multiple soil properties, such as texture, compaction, and presence of vegetation, it is useful to have a large number of samples to estimate the mean value for design of an infiltration practice (Warrick and Nielson 1980; Chowdary et al. 2006).

There are consequences for both overestimation and underestimation of infiltration rate beneath a stormwater control measure (SCM). If infiltration rate is overestimated during the infiltration test, system performance suffers once the SCM is constructed. Volume reduction, mitigation of peak flow rate, and groundwater recharge will all be overestimated during the design phase, resulting in a lack of hydrologic function and pollutant mitigation. Consequences of underestimation of infiltration rate are typically observed in increased construction costs due to the addition of underdrains, deeper bioretention media depths, and reduced ability to utilize internal water storage (submerged) zones as part of the design (Brown et al. 2011). Internal water storage is typically not recommended in HSG D soils or soils with infiltration rates less than 0.05 in/hr.

**Infiltration Rate Measurement Case Studies**

Asleson (2007) summarizes pros and cons of five types of infiltration measurement devices (mini-disk infiltrometer, tension infiltrometer, Guelph permeameter, modified Phillip-Dunne permeameter, and double-ring infiltrometer). In one rain garden, Asleson (2007) estimated an infiltration rate of 0.72 in/hr from 40 mini-disk measurements. Flood test had an average Ksat nearly four times higher, at 2.71 in/hr. Phillip-Dunne and double-ring infiltrometer measurements were near 1 in/hr, suggesting that flood tests of completed bioretention/infiltration devices may be the best method for determining functionality. It appears that current methods of soil infiltration measurements under-predict true media infiltration rate.

Ahmed et al. (2012) attempted to determine a relatively rapid, low cost, low effort approach for determining soil infiltration rate. They performed infiltration measurements on six rain gardens, three turf areas, three swales, an infiltration basin, and proposed rain garden/infiltration areas. They used the Modified Phillip-Dunne infiltrometer to make these measurements. Measurements had large variability (coefficients of variance greater than unity) for all SCM types. Turf had much lower Ksat values than all other SCMs due to soil compaction. The authors contend that due to the high coefficient of variation, 10 to 20 infiltration measurements are needed within a proposed SCM’s footprint to capture the high spatial variability and obtain a median value that will represent the performance of the SCM once it is constructed.

Gulliver and Anderson (2008) provided very detailed descriptions of infiltration measurement device, including: single and double-ring infiltrometers, Guelph permeameters, tension infiltrometers, and Phillip-Dunne Permeameters. In-depth details for how to measure infiltration rates with each device are given, as well as the theory behind the measurements. Equations for calculating infiltration rates based on field measurements with each device are also provided. The authors contest that the most accurate measurement of infiltration rate is post-installation flood testing.

Dorsey (2012) presents an overview of infiltration and the theory behind infiltration into a soil (Darcy’s Law, Green-Ampt Equation, etc). He discusses various non-field estimation methods, including the county soil survey, soil data mart, and soil water characteristic calculator. He then looks at two field methods for infiltration rate measurement – the bore-hole percolation test and double-ring infiltrometer. For bioretention cells, Dorsey recommends one test per 1500 ft2 of infiltrative surface with a minimum of four tests per SCM. All infiltration tests should be completed at the proposed bottom elevation (i.e. location where drainage rock meets the in-situ soil) of the bioretention cell.

Wenck Associates (2008) completed infiltration rate measurements at five infiltration basins with the Coon Creek Watershed District (Minnesota). The authors used both flood tests of the basins and modified Phillip-Dunne permeameter tests to determine infiltration rates for each basin. At two of three sites with data reported, the modified Phillip-Dunne test under-predicted the infiltration rate of the flood test by as much as a factor of sixteen. At the other site, the modified Phillip-Dunne test resulted in an infiltration rate 1.6 in/hr higher than that from the flood test. This suggests that methodologies for soil infiltration rate measurement need to be refined, and we recommend that this be an area that is focused on for future research.

Phillips and Kitsch (2011) compare in-situ methods of infiltration rate measurement at three sites in southern California. Their data set includes those from the pilot infiltration test (common test in Washington state, PIT), double-ring infiltrometer, borehole tests, and hydraulic conductivity estimates (from grain size distributions and cone penetrometer field measurements). The PIT test involved digging a large hole (10 ft by 15 ft bottom dimensions) to the proposed infiltrative surface (bottom of infiltration basin or top of in-situ soil for bioretention cell). Water is then ponded to 2-4 feet rapidly, and maintained at a constant head for a minimum of 24 hours. The water flow rate necessary to maintain this constant water level is recorded as the infiltration rate of the soil. The authors contend that the PIT test is the most rigorous known method of infiltration measurement, and that it provides the most accurate pre-construction estimation of infiltration rate. However, measurements made using the PIT test are laborious, costly, and time-consuming.

**Types of Infiltration Measurement Devices**

Various devices are available for measurement of infiltration within a proposed SCM, including the single ring infiltrometer, double ring infiltrometer, Philip-Dunne permeameter, Guelph permeameter, and tension infiltrometer. Some infiltration measurement devices also require soil moisture to be measured, which may be measured using methods in Klute (1986). A detailed description of each technique for infiltration rate measurement, including methods and required post-processing, may be found in Gulliver et al. (2010). Methods typically use either a constant or falling head of water above the infiltrative surface (Table 1). Measurements of infiltrated volume as a function of time are made, with design infiltration rate or intake rate taken as the infiltration rate once the measurement has approached a horizontal asymptote (see Figure 1).

Table 1. Qualitative comparison of various methods of infiltration rate measurement (adapted from Asleson, 2007)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Criteria | Double Ring Infiltrometer | Single Ring Infiltrometer | Philip Dunne Permeameter | Minidisk Infiltrometer | Guelph Permeameter | Tension Infiltrometer |
| Equipment Transportability | Medium | Easy | Easy | Easy | Medium | Difficult |
| Volume of Water Needed | Medium | Low-Medium | Low | Low | Medium | High |
| Time (hrs) | Medium-High | Medium | Medium | Low | High | Medium |
| Personnel (#) | 1-2 | 1-2 | 1 | 1 | 2 | 2 |
| Cost | Medium | Low-Medium | Low | Low | High | High |
| Other advantages | ASTM D3385 standard for measurement | Simpler to use than double ring infiltrometer | Easy to install in ground. Multiple measurements can be made quickly. | Simplest of devices | May be used to measure infiltration at depth (up to 2.5 ft) | Measure unsaturated hydraulic properties of soil |
| Other disadvantages | Requires large volume of water in permeable soils | Requires large diameter to be accurate (minimize edge effects) | Need to measure initial and final soil moisture content | Small diameter -many measurements need to be made to ensure accuracy | Small diameter -many measurements need to be made to ensure accuracy | Typically need a sand base to ensure contact between soil and infiltrometer |

Design Infiltration Rate

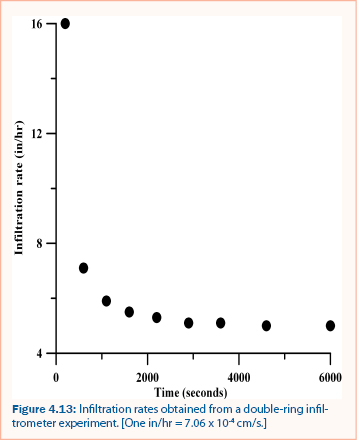


Figure 4.1: Example of data from a field infiltration rate measurement with a double ring infiltrometer [source: adapted from Gulliver et al. (2010)]. Design infiltration rate is shown on the figure.

**Soil Infiltration Rate Measurement Techniques**

Because of the potential for 3-dimensional flow in a bore hole percolation test (wherein water is flooded into a bore hole and flow rate measured), this method should not be used when designing a stormwater infiltration device. A method which mirrors the one-dimensional exfiltration from a bioretention cell or infiltration device is desired.

Typically, these measurements are made with an infiltrometer – a circular device which allows water to be ponded on the soil surface. Measurements may be taken as a function of time to determine the design infiltration rate of the soil. For instance, ASTM D3385 (2003) describes field measurement of infiltration rate using the double ring infiltrometer method. The primary reason for the secondary, outer ring is to reduce edge effects and produce one-dimensional, vertical flow in the inner ring, where measurements of depth as a function of time are made. Some researchers have observed that field, laboratory, and numerical modeling tests have shown a large diameter, single ring infiltrometer provides measurements that are of similar accuracy to the double ring test (Bouwer, 1986; Reynolds et al. 2002). Another study showed that measurements of infiltration rate with single ring infiltrometers were slightly higher than those of a double ring infiltrometer, but the measurements were not significantly different (Walsh and McDonnell, 2012). Single ring cylinders should be as large in diameter as possible to obtain accurate results, with diameter of 3 feet or more preferable (Bouwer, 1986). Tests should be run until a constant intake rate (in/hr) into the soil is achieved. However, no ASTM standard is available for single ring infiltrometer measurements.

Another method for estimating the soil infiltration rate is the Modified Phillip-Dunne Permeameter, which was developed by the University of Minnesota. It makes use of a falling head test within a single metal cylinder pounded 2 inches into the soil to determine infiltration rate. An initial soil moisture content measurement must be made, and then the cylinder is filled with water. As the permeameter drains, measurements of stage and time are taken. Then, a final measurement of soil moisture content is aggregated into a post-processing spreadsheet, where saturated hydraulic conductivity is calculated.

**Soil Property Determination for Infiltration SCM design**

Designers should evaluate soil properties during preliminary site layout with the intent of installing bioretention or bioinfiltration practices on soils with the highest infiltration rates (HSG A and B). Preliminary planning for the location of an infiltration device may be completed using a county soil survey or the NRCS Web Soil Survey (<http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>). These publications provide HSG information for soils across Minnesota. To ensure long-term performance, however, field soil measurements are desired to provide site-specific data.

All soil analysis and infiltration testing must be completed within the proposed boundary of the SCM. Soil borings for building structural analysis will not be acceptable.

In all design scenarios, a minimum of one soil boring (two are recommended) shall be completed to a depth 3 feet below the bottom of the proposed bioretention SCM (Dakota County Soil and Water Conservation District, 2012) per ASTM D1586 (ASTM, 2011). For bioretention SCMs with surface area between 1000 and 5000 ft2, two borings shall be made. Between 5000 and 10000 ft2, three borings are needed, and for systems with greater than 10000 ft2 in surface area, 4 or more borings are needed. For each additional 2500 ft2 beyond 12,500 ft2, an additional soil boring should be made (Table 2). Soil borings must be undertaken during the design phase (i.e. prior to the commencement of construction) to determine how extensive the soil testing will be during construction. Borings should be completed using continuous split spoon sampling, with blow counts being recorded to determine the level of compaction of the soil. Soil borings are needed to understand soil types, seasonally high groundwater table elevation, depth to karst, and bedrock elevations. Soil profiles should be recorded for each layer encountered in the boring, including information on soil texture, Munsell soil color, redoximorphic features, soil structure, occurrence and abundance of roots, and occurrence of saturated soils or lenses.

For design purposes, there are two ways of determining the soil infiltration rate. The first, and preferred method, is to field-test the soil infiltration rate using appropriate methods described below. The other method uses the typical infiltration rate of the most restrictive underlying soil (determined during soil borings) as stated in the MN Stormwater Manual (Table 3 herein).

If infiltration rate measurements are made, a minimum of one infiltration test in a soil pit must be completed at the elevation from which exfiltration would occur (i.e. interface of gravel drainage layer and *in situ* soil). When the SCM surface area is between 1000 and 5000 ft2, two soil pit measurements are needed. Between 5000 and 10000 ft2 of surface area, a total of three soil pit infiltration measurements should be made. Each additional 5000 ft2 of surface area triggers an additional soil pit (Table 2). The median measured infiltration rate should be utilized for design. Soil pits should be dug during the design phase and should be a minimum of two feet in diameter for measurement of infiltration rate. Infiltration testing in the soil pit can be completed with a double-ring infiltrometer or by filling the pit with water and measuring stage vs. time. If the infiltration rate in the first pit is greater than 2 in/hr, no additional pits shall be needed.

Alternatively, a Modified Philip-Dunne permeameter can be used to field test infiltration rate. Guidance for the number of permeameter tests required based on bioretention surface area is given in Table 2. Modified Philip-Dunne permeameter tests may be made in conjunction with soil borings or may be completed using a handheld soil auger. Borings should be lined with a plastic sleeve to prevent infiltration from the sides of the borehole (i.e. restrict flow to vertical infiltration). Soil borings should be filled with water. The time for the borehole to drain should be recorded and divided by the initial ponding depth in the borehole to provide an infiltration rate measurement. The design infiltration rate should be the lower of the median soil pit infiltration rate or the median borehole method infiltration rate.

Table 2. Soil boring, pits, and permeameter tests for bioretention design.

|  |  |  |  |
| --- | --- | --- | --- |
| **Surface area of SCM (ft2)** | **Borings** | **Pits** | **Permeameter** |
| < 1000 | 1 | 1 | 5 |
| 1000 to 5000 | 2 | 2 | 10 |
| 5000 to 10000 | 3 | 3 | 15 |
| > 10,000 | 4 1 | 4 1 | 20 2 |

1 an additional soil boring or pit should be completed for each additional 2,500 ft2 above 12,500 ft2

2 an additional five permeameter tests should be completed for each additional 5,000 ft2 above 15,000 ft2

Table 3. Design infiltration rate as a function of soil texture for bioretention in Minnesota.

|  |  |  |
| --- | --- | --- |
| **Soil texture** | **Corresponding Unified Soil Classification** | **Design Infiltration Rate (in/hr)** |
| Gravel, sandy gravel, and silty gravels | **GW** – Well-graded gravel or well-graded gravel with sand  **GP** – Poorly graded gravel or poorly graded gravel with sand | 1.63 |
| Sand, loamy sand, and sandy loam | **GM** – Silty gravel or silty gravel with sand  **SW** – Well-graded sand or well-graded sand with gravel  **SP** – Poorly graded sand or poorly graded sand with gravel | 0.8 |
| Silt loam | **SM** – Silty sand or silty sand with gravel | 0.3 |
| Loam | **ML** – Silt  **OL** – Organic silt or organic silt with sand or gravel or gravelly organic silt | 0.3 |
| Sandy clay loam | **GC** – Clayey gravel or clayey gravel with sand  **SC** – Clayey sand or clayey sand with gravel | 0.2 |
| Clay, clay loam, silty clay loam, sandy clay, and silty clay | **CL** – Lean clay or lean clay with sand or gravel or gravelly lean clay  **CH** – Fat clay or fat clay with sand or gravel or gravelly fat clay  **OH** – Organic clay or organic clay with sand or gravel or gravelly organic clay  MH – Elastic silt or elastic silt with sand or gravel | 0.06 |

**Test for Bioretention Cell Acceptance**

Post-construction, it is important to field-test the drawdown rate of the bioretention cell to determine whether it is functioning as intended (Wenck Associates, 2008). This is the most accurate method to determine if a bioretention cell is correctly functioning, since it accounts for spatial variability in infiltration rates. Post-construction, bioretention cells and infiltration devices should be flooded with water and the time for complete drawdown to occur (i.e. no standing water in the bowl) should be recorded. An electronic stage recorder, a staff gage and wildlife camera, or a pulley float stage recorder may be used to measure drawdown. By taking the quotient of initial water depth to drawdown time, an estimation of drawdown rate can be obtained. The device may be either flooded with water from a fire hydrant or other source, or a natural rainfall event which fills the bowl entirely may also be utilized for this purpose. Media drawdown rates should fall between 1 in/hr and 8 in/hr immediately after construction to meet acceptance criteria.

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